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### Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems

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# Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems

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**Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems**

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## Abstract

Soils are warming as air temperatures rise across the Arctic and Boreal region concurrent with the expansion of tall-statured shrubs and trees in the tundra. Changes in vegetation structure and function are expected to alter soil thermal regimes, thereby modifying climate feedbacks related to permafrost thaw and carbon cycling. However, current understanding of vegetation impacts on soil temperature is limited to local or regional scales and lacks the generality necessary to predict soil warming and permafrost stability on a pan-Arctic scale. Here we synthesize shallow soil and air temperature observations with broad spatial and temporal coverage collected across 106 sites representing nine different vegetation types in the permafrost region. We showed ecosystems with tall-statured shrubs and trees ( $> 40$  cm) have warmer shallow soils than those with short-statured tundra vegetation when normalized to a constant air temperature. In tree and tall shrub vegetation types, cooler temperatures in the warm season do not lead to cooler mean annual soil temperature indicating that ground thermal regimes in the cold-season rather than the warm-season are most critical for predicting soil warming in ecosystems underlain by permafrost. Our results suggest that the expansion of tall shrubs and trees into tundra regions can amplify shallow soil warming, and could increase the potential for increased seasonal thaw depth and increase soil carbon cycling rates and lead to increased carbon dioxide loss and further permafrost thaw.

**Introduction**

Rapid increases in air temperature across the Arctic and Boreal region are associated with warming soils, thawing permafrost, and expanding tall-statured shrubs and trees in the tundra (Romanovsky *et al.*, 2003; Myers-Smith *et al.*, 2011; Elmendorf *et al.*, 2012). Warming soils place the vast pool of carbon frozen in permafrost at risk of thawing and releasing greenhouse gases into the atmosphere (Schuur *et al.*, 2015; Biskaborn *et al.*, 2019). Warming soils also impact belowground plant function and root growth (Iversen *et al.*, 2015), modifying plant nutrient use, primary productivity, and transpiration (Cable *et al.*, 2014; Lafleur & Humphreys, 2018; Hewitt *et al.*, 2019). Warmer soils and deeper seasonal thaw alter soil nutrient and carbon cycling (Keuper *et al.*, 2012; Salmon *et al.*, 2015; Finger *et al.*, 2016). Thus, quantifying the degree of soil warming is critical to understanding future ecosystem function and the stability of underlying permafrost (Jorgenson *et al.*, 2001; Lorant *et al.*, 2018).

Vegetation change across the pan-Arctic is altering land surface energy dynamics with critical implications for soil thermal regimes in the permafrost region (Elmendorf *et al.*, 2012; Myers-Smith *et al.*, 2015; Martin *et al.*, 2017). Experimental manipulations of shrub cover in tundra ecosystems indicate that increasing shrub canopy (“shrubification”) cover reduces summer soil temperatures and decreases the depth of seasonal thaw via canopy shading (Blok *et al.*, 2010; Myers-Smith & Hik, 2013). In contrast, a recent study using eddy covariance measurements suggests that shrubs are associated with warmer summer soil temperatures (Lafleur & Humphreys, 2018). Shrubs increase winter soil temperatures due to insulation by trapping snow (Myers-Smith *et al.*, 2015). The net effect on annual thermal regimes may depend on local and seasonal environmental conditions including microclimate, topography, and soil properties (Zellweger *et al.*, 2020), and individual plot scale studies provide limited insight. The

134 lack of consensus in plot scale observations creates uncertainty regarding potential feedbacks of  
135 shrubification in the tundra, and calls for a larger scale assessment of the impacts of vegetation  
136 on soil temperature.

137 Treeline advance may have similar soil temperature consequences to shrub expansion  
138 since observations indicate that greater tree leaf area is associated with decreased summer thaw  
139 depths (Fisher *et al.*, 2016). Associations between boreal forest cover and snow depth have also  
140 been related to warmer winter soil temperatures (Jean & Payette, 2014). However, the effects of  
141 changing forest cover on soil temperatures has received considerably less attention compared to  
142 shrub expansion studies. This is an important knowledge gap as links between vegetation  
143 structure and soil thermal dynamics are critical for assessing the vulnerability of permafrost to  
144 ongoing climate warming and vegetation shifts (Lawrence *et al.*, 2012; Cable *et al.*, 2016).

145 The current understanding of boreal and tundra vegetation impacts on soil temperature is  
146 limited to local or regional scales (Blok *et al.*, 2010; Fisher *et al.*, 2016; Paradis *et al.*, 2016;  
147 Frost *et al.*, 2018) and lacks the generality necessary to predict soil warming and permafrost  
148 stability on a pan-Arctic scale. The net effects of vegetation on annual thermal regimes may also  
149 reflect local and seasonal meteorological and soil conditions. A synthesis of high-latitude studies  
150 with broader geographic coverage and greater variability in soil and site conditions can offer the  
151 potential to evaluate whether plot scale observations of vegetation impacts on soil temperature  
152 are consistent across studies within similar types of vegetation (Fidler *et al.*, 2017). Here we  
153 establish empirical linkages between observations of vegetation and air-soil temperatures using  
154 106 sites located within nine common Arctic and Boreal vegetation types (Walker *et al.*, 2005) to  
155 address the following questions: *i*) do shrubs and trees cool shallow soils during the warm



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season? *ii*) how does vegetation affect cold season soil temperatures? *iii*) does vegetation influence the seasonal dynamics of soil temperature on annual timescales?

**Methods**

*Temperature Data*

Daily average soil and air temperature was compiled from 235 sites across the Arctic-boreal region that are underlain by permafrost and that include a vegetation description at the study locations. We compiled a total of 877,305 soil temperature observations and 304,492 air temperature observations. Figure 1 displays the pan-Arctic permafrost extent (Brown *et al.*, 2011) with study sites to provide context. Table 1 contains a full break down of the number of observations and sites for each vegetation type and Table S1 (Electronic Supplement) contains site descriptions for all sites used in analysis, and Table S2 (Electronic Supplement) information for all 235 sites initially compiled.

Our analysis focused on a total of 106 sites with 305,973 soil and 169,362 air temperature observations that met the following considerations to achieve a harmonized analysis, and the remaining 129 sites originally compiled were not used in the analysis. The 106 sites used in the analysis were selected based on the criteria explained below. We focused only on soil temperature measured within the top 20 cm of the active layer, and sites without observations in the upper 20 cm were not included. We focus on the temperature in the upper 20 cm of the active layer has the closest coupling to the air temperature and influences the temperature of the soil below (Smith & Riseborough, 1996; Hillel, 1998). An initial analysis demonstrated that soil temperature varies nonlinearly at depths below 20 cm, and this nonlinear relationship can be highly variable between sites. Our sample size of sites with data below 20 cm was too limited to

adequately characterize these deeper depths across the study domain, and thus any sites that did not make observations in the upper 20 cm of the soil were excluded. Air temperature measurements also needed to be taken from a minimum height of 1 m to avoid measurements within the snow during the winter. Sites with air temperature sensors mounted below 1 m in height above the ground were excluded. We use water years (Oct-Sept) rather than the calendar year to characterize annual temperature patterns since winter soil temperatures will be highly dependent on autumn soil temperature and snow accumulation. Sites needed at least 75% of a water year with observations to be included in the study. To avoid confusion with calendar year seasons and the ambiguity of defining transition periods, we define seasonality based on when site temperatures are below freezing (cold season) and above freezing (warm season).

### *Vegetation Data*

Each site was classified into a vegetation type based on the growth form of the dominant plant cover. We classified tundra plant communities similar to the broad physiognomic categories that vegetation communities are grouped in by Walker *et. al.* (2016) to allow for our results to be placed into broader geographical contexts. Boreal vegetation classes were classified by leaf functional type of the dominate tree cover including evergreen needleleaf boreal forest, deciduous needleleaf boreal forest, and mixed evergreen needleleaf and deciduous broadleaf boreal forest. Tundra vegetation types include herb barren, graminoid tundra (non-tussock forming), short shrub tundra (<40 cm in height), tussock tundra, tall shrub tundra (>40 cm in height), and wetland. Here we separated wetland as any vegetation type that experiences inundation throughout the duration of the warm season rather than a single plant functional type deviating from Walker *et. al.* (2016). We also simplified shrub categories from Walker *et. al.*

(2016) including all dwarf and prostrate shrubs in our short shrub category and all tall shrubs defined as above >40 cm. Herb-barren and deciduous needleleaf have limited geographic scope with a few sites located in close proximity. We included these sites for comparison, but caution against broader geographic extrapolation.

*Soil and Air temperature models*

Many sites have incomplete observations of air or soil temperature throughout a water year due to the timing of sensor deployment or sensor failure. We implemented a phenomenological model of daily soil temperature in a Bayesian framework to account for missing observations. We used this model to gap fill missing temperature observations in the sites with 25% or less missing data in a water year. Using a statistical modelling approach allowed us to avoid bias in metrics such as mean annual, maximum, and minimum temperatures that can be heavily biased with missing observations and quantify uncertainty in these metrics. This modelling approach also provided a quantitative comparison of annual soil temperature patterns throughout a water year, and these parameters can be compared between sites in empirical models to better understand variabilities in air-soil temperature decoupling. A full description of the daily soil and air temperature model is included in the electronic supplement.

*Empirical Vegetation-Temperature Relationships*

We implemented empirical models of air and soil annual temperature parameters (maximum, minimum, and mean annual soil temperature) to evaluate the influence of vegetation on air-soil temperature decoupling. We compared differences between the air and soil minimum

and maximum temperature in a year and the number of days in the water year that were above zero across sites. We used a normalized measure of air and soil temperature decoupling to understand the cumulative decoupling of temperatures above and below freezing (Smith & Riseborough, 1996, 2002). The n-factor for the freezing degree day soil:air ratio ( $n_f$ ) was calculated from the degree days below freezing ( $FDD$ ), and the thawing n factor ( $n_t$ ) was calculated from the degree days above freezing ( $TDD$ ):

$$n_f = \frac{FDD_{soil}}{FDD_{air}}$$

$$n_t = \frac{TDD_{soil}}{TDD_{air}}$$

We implemented multiple regressions in a Bayesian framework to evaluate empirical relationships between vegetation type and soil temperature parameters. We included the uncertainty from the air and soil temperature model in the empirical models of temperature parameters and n-factors that had missing observations using a Berkson error model to account for uncertainty in parameters. A multiple linear regression was conducted in a hierarchical Bayesian framework with the corresponding air temperature parameter and depth of measurement used as covariates and the vegetation type treated as fixed effects. This approach allowed us to compare soil temperature parameters between vegetation types while controlling for air temperature and sensor placement. Since we compare multiple soil temperature parameters between nine vegetation groups, we used a Bonferroni correction on credible intervals for any statistical inferences made between groups to help account for the many comparisons in this analysis (Ogle *et al.*, 2019).

**Results**

*Soil and Air Temperature Models*

The daily soil temperature model had a model fit with  $R^2$  of 0.95 (Figure S1, Electronic Supplement). Soil temperature data were slightly over-predicted at low temperatures ( $< -15\text{ }^{\circ}\text{C}$ ) and under-predicted at higher temperatures with a least squares regression intercept of  $-0.09$  at an observed temperature of  $0\text{ }^{\circ}\text{C}$  and slope of  $0.95\text{ }^{\circ}\text{C}$  per one  $^{\circ}\text{C}$  increase in observed soil temperature. The daily air temperature model fit had a  $R^2$  of 0.83 (Figure S1, Electronic Supplement). Air temperature data were slightly over-predicted at low temperatures ( $< -10\text{ }^{\circ}\text{C}$ ) and under-predicted at higher temperatures with a least squares regression intercept of  $-1\text{ }^{\circ}\text{C}$  at an observed temperature of  $0\text{ }^{\circ}\text{C}$  and slope of  $0.83\text{ }^{\circ}\text{C}$  per one  $^{\circ}\text{C}$  increase in observed soil temperature. The empirical models of annual temperature measures with vegetation type, depth in soil, and annual air temperature measures had model fits with  $R^2$  of 0.69 for minimum soil temperature,  $R^2$  of 0.70 for maximum soil temperature, and  $R^2$  of 0.72 for mean annual soil temperature (Figure S2). Bivariate plots of the relationship between the air and soil temperatures in these empirical models are shown in Fig. S3. Models accounting for soil depth within each vegetation type for the n-factors, and the length of days above freezing had model fits with  $R^2 = 0.51, 0.69$ , and  $0.28$  respectively (Figure S4).

*Warm Season Soil Temperatures*

Boreal forests and tussock tundra have lower soil temperatures in the warm season than other tundra vegetation types after accounting for air temperature and the depth of measurement. In above-freezing conditions, soil temperatures are highly decoupled from the air with a thawing n-factor at the soil surface (0 cm) far below one in boreal forests (Fig 3a) with a ratio of 0.73

[Bonferroni adjusted 95% Credible Interval (CI): 0.54, 0.90] for evergreen needleleaf and 0.53 [CI 0.38, 0.67] for deciduous needleleaf forests. Tussock tundra soil temperatures showed the greatest degree of decoupling from air temperatures compared to all other tundra types with a ratio of 0.81 [CI 0.76, 0.87]. Soils in herb-barren, graminoid tundra, and tall shrub tundra tended to be similar or warmer than the air with a thawing n-factor at or above one (Fig 3a).

Soil temperatures remain above-freezing for the longest time period in boreal forests, wetlands, short shrub tundra, and tussock tundra with a statistically similar length of time ranging between 160-174 days on average (Fig 3b). Under the same air temperature maximum of 12 °C and at the soil surface (0 cm), deciduous needleleaf boreal forests had the lowest maximum soil temperatures that were roughly 5°C lower than the air [6.9; CI 4.2,10.3]. Tall shrub tundra had slightly higher maximum soil temperatures than the air [12.7 °C; CI 12.1, 13.2], and higher maximum soil temperatures than graminoid tundra [11.1 °C; CI 10.8, 11.5]. The similarity in the length of days above-freezing between different vegetation types suggests that differences in warm season soil temperature coupling to the air temperature is driven by magnitude of the maximum soil temperature rather than the length of time above freezing.

### *Cold Season Soil Temperatures*

Short shrub tundra, graminoid tundra, and herb-barren had the lowest soil temperatures in the cold season and all other vegetation types had similar soil temperatures despite broad differences in canopy height and characteristics between these vegetation types. The freezing n-factors indicated that tall shrub, tussock, wetlands, and boreal forest soils were much warmer than the air with the highest decoupling from air temperatures (Fig. 4a), varying between 0.30 [CI 0.12, 0.47] in deciduous needleleaf forests and 0.39 [CI 0.35, 0.43] in tall shrub tundra. Short

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3 290 shrub and graminoid tundra had much closer coupling of freezing soil temperatures to the air  
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5 291 with freezing n-factors of 0.62 [CI 0.57, 0.68] and 0.58 [CI 0.55, 0.62] respectively. Herb-barren  
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7 292 soils were colder than the air with a freezing n-factor of 1.2 [CI 1.11, 1.29].  
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10 293 Patterns in minimum soil temperature followed similar patterns as the freezing degree  
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12 294 day ratios with herb barren, short shrub tundra, and graminoid tundra experiencing the lowest  
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14 295 temperatures. Under a standardized air temperature of -22 °C and at the soil surface (0 cm),  
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16 296 minimum soil temperatures were -13.8 °C [CI -14.7, -12.9] in graminoid tundra and -15 °C [CI -  
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18 297 16.1, -13.9]. Soil temperatures were much higher than the air in boreal forests with evergreen  
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20 298 needleleaf at -7.3 [CI -11.6, -3.4] °C and deciduous needleleaf at -1.9 [CI -10.6, 10] °C. Tall  
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22 299 shrub and tussock tundra had similar minimum soil temperatures of -8.8 °C [CI -9.7, -7.9 and CI  
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24 300 -9.9, -7.6 respectively]. Long-term patterns of winter precipitation derived from WorldClim data  
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26 301 illustrate greater variability within than between vegetation types (Fig. S5), suggesting that  
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28 302 geographic patterns in snowfall do not contribute to winter soil temperature patterns that we  
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30 303 observe. We also found overlap in latitude and air temperatures (Fig S6-8) in most vegetation  
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32 304 types indicating that potential differences between vegetation types likely do not reflect regional  
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34 305 or climatic patterns for most vegetation types.  
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42 307 *Annual Soil Temperature Dynamics*  
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44 308 Ecosystems with vegetation with very short canopies (< 40 cm: herb barren, graminoid,  
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46 309 and short shrub tundra) have the lowest mean annual soil temperatures compared to ecosystems  
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48 310 characterized by trees or tall shrub vegetation types (Fig. 4c). Patterns in mean annual  
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50 311 temperature closely followed patterns in minimum soil temperature (Fig 4b and 4c). At a  
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52 312 standardized mean annual air temperature of -6 °C, mean annual soil temperatures in short shrub  
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and graminoid tundra are -2.8 °C [CI -3.3, -2.4] and -2.5 °C [CI -2.9, -2.2] respectively, approximately two degrees lower than mean annual soil temperatures in evergreen needleleaf boreal forests and tall shrub tundra (Figure. 4c).

Variation in mean annual soil temperature is primarily driven by the minimum soil temperature in the cold season (Figure 5a and b) in all vegetation types, and is likely linked to the latent heat exchange necessary for warming frozen soil. Surprisingly, summer maximum soil temperatures showed weak relationships (Figure 5c and d, Tables S3 & S4), explaining 9-50% of variability in mean annual temperature in most tundra vegetation types with the exception of herb-barren and tall shrub tundra. Mean annual soil temperature and maximum soil temperatures were closely related in ( $R^2 = 0.80$ ) in herb-barren. There was no significant relationship in tall shrub tundra. Mean annual soil temperature was also not significantly related to maximum soil temperatures in all boreal forest types indicating that warmer summer conditions do not necessarily increase mean annual temperatures. Maximum soil temperature was not significantly related to minimum soil temperature with the exception of tall shrub tundra (electronic supplement, Fig S9). Colder minimum temperatures were associated with warmer maximum temperatures in tall shrub tundra. This demonstrates that for many vegetation types, cold season conditions predominately drive mean annual soil temperatures, and there is not a strong coupling between cold season and warm season soil temperatures.

## Discussion

### *Impacts of Vegetation on Cold- and Warm-Season Soil Temperature*

We found that tall shrub tundra had the highest soil temperatures after herb-barren during the warm season (Figure 3a,b,c) when normalized by air temperature, contrary to observations of



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3 336 local soil cooling associated with shading from shrubs in the warm season (Blok *et al.*, 2010;  
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5 337 Loranty *et al.*, 2018). Short shrub tundra also had higher temperatures than boreal forests and  
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7 338 tussock tundra. Tall and short shrub ecosystems do not reflect the localized cooling effect of  
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10 339 shading observed by other studies (Sturm *et al.*, 2001; Hinzman *et al.*, 2005; Myers-smith *et al.*,  
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12 340 2011), but rather exhibited relatively tight coupling with warm season air temperatures.  
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15 341 Consequently, record high summer air temperatures across the Arctic (Serreze & Barry, 2011;  
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17 342 Overland *et al.*, 2017) may have a greater impact on warm season ecosystem processes such as  
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19 343 plant phenology and productivity and nutrient dynamics in tundra ecosystems compared to  
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21 344 boreal ecosystems (Loranty *et al.*, 2018; Post *et al.*, 2019). The cooling impact of shrubs during  
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23 345 summer observed in manipulation experiments (Blok *et al.*, 2010; Myers-Smith & Hik, 2013;  
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25 346 Nauta *et al.*, 2015), likely describes a highly localized microclimate effect that is limited to  
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27 347 directly below the shrub canopy (Lantz *et al.*, 2013). Our results indicate that such microclimate  
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29 348 effects are awash in a larger dataset that includes a broader range of measurement probe  
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31 349 locations within the ecosystem and varied meteorological conditions. As such, we acknowledge  
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33 350 the limited geographic scope of herb-barren and deciduous needleleaf forest in this study are not  
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35 351 necessarily representative of pan-Arctic wide patterns. Our results highlight that individual plot  
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37 352 scale results in the warm season are highly localized results and measurements in localized  
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39 353 regions are not suitable for broadly generalizing how vegetation can impact soil temperatures  
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41 354 across the permafrost region.

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47 355 We found that cold season soil temperatures were more consistent between vegetation  
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49 356 types compared to the warm season, and vegetation types that are characterized by short  
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51 357 canopies had the lowest temperatures after controlling for air temperature. While we were unable  
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54 358 to control for snow cover in our analyses, the broad geographic and climatological ranges

captured by our sample sites (Figs. S6-S9) indicate that our results do not reflect regional variation in snowfall. Vegetation affects cold season soil temperatures through impacts on snow distribution and snowpack characteristics (Essery & Pomeroy, 2004; Myers-smith *et al.*, 2011). Greater shrub height (Paradis *et al.*, 2016; Frost *et al.*, 2018) and higher forest cover (Jean & Payette, 2014) are directly linked to higher winter soil temperatures, but we observe similarly high cold-season soil temperatures across all tall shrubs and trees. The insulating effect of snow on soil temperatures saturates at snow depths as low as 20 cm (Slater *et al.*, 2017), and thus geographic variation in snow cover or large differences in canopy height between the shrubs and trees in our study may have minimal influence across our broad geographical scope.

#### *Vegetation and Soil Temperature on Annual Timescales*

Overall, we found that annual soil thermal regimes in the permafrost region are dominated by cold season conditions likely due to physical processes associated with frozen soils such as higher thermal conductivity in frozen soils, the amount of latent heat necessary to thaw soils, the influence of snow meltwater in the spring, and the release of latent heat in freezing soils (Shur & Jorgenson, 2007; Throop *et al.*, 2012). Herb barren was the only vegetation type where both minimum and maximum temperatures were highly correlated with the mean annual soil temperatures as is typical for annual fluctuations in soil temperature (Hillel, 1998). Annual patterns in soil temperature have a longer duration of the cold season than the warm season (Fig. 2, Fig. 3b) and soils in all vegetation types excluding herb-barren had some sites that experienced a zero curtain. The zero curtain is characterized by a prolonged time period (days-months) when temperatures linger near zero due to latent heat associated with freeze/thaw or the addition of snow meltwater into the soil (Fig 2). Mean annual soil temperature did not

significantly vary with warm season maximum temperatures in boreal and tall shrub tundra suggesting that mean annual conditions are more sensitive to temperature changes in the cold season.

Surprisingly, higher winter soil temperatures were not associated with higher summer soil temperatures with no relationship between minimum and maximum temperatures in all vegetation types except for tall shrub tundra (Figure S5). Sites with colder minimum temperatures tended to have warmer maximum temperatures in tall shrub tundra. It is likely that sites with warmer minimum temperatures and colder maximum temperatures could experience prolonged periods of freeze/thaw cycles due to high water content in the soil (Outcalt *et al.*, 1990; Romanovsky & Osterkamp, 2000). This indicates that soil thermal characteristics and snow that influence coupling with air temperature are likely a driving factor in seasonal soil temperature amplitude (Nicholson, 1979; Smith & Riseborough, 1996;). Further assessment of seasonal soil heat fluxes, soil moisture conditions, and vegetative traits and function would help elucidate the plot level seasonal drivers of temperature (Loranty *et al.*, 2018). In our synthesis, we found a paucity of data that simultaneously quantified vegetation composition and structure, soil moisture, soil, and snow properties. These inconsistencies are compounded by variation in duration of data availability, measurement height or depth in soil and air temperature measurements. While our modelling approach allowed us to overcome many of these issues, it is clear there is a continued need for better understanding the biological and physical drivers of soil-vegetation-atmosphere continuum coupling in the permafrost region, especially those related to interactions between vegetation canopies and snow cover.

*Soil temperature and climate change*

Our results indicate that ongoing vegetation change across the Arctic will alter relationships between air and soil temperatures with continued climate warming. Widespread tree and shrub expansion are among the most prominent changes, and will accelerate soil warming (Chapin III *et al.*, 2000; Tape *et al.*, 2006; Pearson *et al.*, 2013; Frost & Epstein, 2014). However, emerging evidence indicates that pan-Arctic vegetation change is not unidirectional (Phoenix & Bjerke, 2016). Advances in long-term monitoring and remote sensing technologies have revealed heterogeneity in Arctic vegetation change typically inferred by time series analyses of satellite data (Myers-Smith *et al.*, 2020). In boreal forests, disturbances such as fire and permafrost thaw may lead to net declines in forest cover at the landscape scale (Helbig *et al.*, 2016; Sniderhan & Baltzer, 2016). Consequently, accurate predictive understanding of future pan-Arctic soil temperature regimes, and associated impacts on permafrost and related climate feedbacks will require detailed understanding of vegetation dynamics. The contrary outcomes between some plot-scale shrub manipulations and our results demonstrates that small scale (meters-kilometers) spatial heterogeneity around plant canopies likely impacts soil temperatures (Palmer *et al.* 2012). Our synthesis of plot scale observations demonstrates that there are clear differences between trees, tall shrubs, and short tundra vegetation at larger spatial scales, but we cannot discern the causal mechanisms underlying these differences from our data alone. Our study suggests that a better understanding of the spatial heterogeneity in snow and soil conditions around plant canopies would lead to a better understanding of the impacts of vegetation on ground thermal regimes. Standardized and consistent methodological approaches that concurrently measure vegetation, snow, soil properties, and hydrologic conditions from plot to ecosystem scales with spatial coverage throughout the pan-Arctic and boreal regions would greatly enhance the causal understanding of vegetation impacts on soil temperature.

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Permafrost temperatures are rising as the Arctic experiences increases in air temperature (Hinzman *et al.*, 2005; Romanovsky *et al.*, 2010), but rates of temperature increase vary with local hydrological conditions, soil thermal properties, and vegetation characteristics (Jorgenson *et al.*, 2001; Romanovsky *et al.*, 2010; Cable *et al.*, 2016). The mean annual temperature of the permafrost table is typically correlated with the mean annual temperature of the ground surface (Smith & Riseborough, 1996; Romanovsky *et al.*, 2003). Our measures of mean annual surface soil temperature have implications for permafrost temperatures, but permafrost temperatures ultimately depend on both surface thermal dynamics and characteristics that affect heat transfer in the soil such as thermal conductivity and moisture content (Smith & Riseborough, 1996; Cable *et al.*, 2016). Our work, for instance, does not quantify vegetation impacts on soil thermal conductivity (such as transpiration- driven soil drying that reduces conductivity), which might decouple the influence of warming surface soil temperatures on permafrost (Lorantý *et al.*, 2018).

During the cold season, soil respiration is a significant source of carbon dioxide and can increase by a factor of 2.9-8.5 per 10° C increase in winter soil temperature (Natali *et al.*, 2019). Our observations demonstrate that minimum soil temperatures are 4-20° C greater in tall shrub and tree vegetation types relative to short-statured vegetation types under the same air temperature. Though we cannot rule out the possibility that soil temperature increases preceded vegetation change, our results nonetheless imply that observed vegetation change across the Arctic may be associated with increased winter greenhouse gas emissions from soil respiration in recent decades. In the long term (centuries to millennia), soil warming that results in permafrost degradation and soil warming will alter carbon accumulation (Swanson *et al.* 2000). Overall, continued increases in vegetation height associated with tall shrub and trees expansion over the

next century (Myers-smith *et al.*, 2011; Elmendorf *et al.*, 2012) lead to warmer shallow soils and increase the potential for a permafrost carbon climate feedback.

Vegetation change across the Arctic has the potential to affect the coupling between air and soil temperatures, with important implications for soil and carbon dynamics in permafrost regions. Numerous field studies have provided insights regarding the direction and magnitude of soil temperature changes associated with vegetation transitions, primarily at the seasonal timescale. Our pan-Arctic synthesis reveals that trees and shrubs promote warmer shallow soil temperatures at annual timescales, mainly due to warmer cold-season soil temperatures. Summer air temperatures do not have strong impacts on annual soil temperature dynamics, and so will primarily affect seasonal plant function and soil carbon dynamics in most tundra vegetation types. Tree and shrub expansion will amplify the effects of climate warming on soil temperature potentially leading to increases in winter carbon emissions and could increase permafrost temperature and thaw.

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**Author contributions:**

H.K., M.L., and S.M.N. conceived the work. H.K. performed data analysis and generated figures. H.K., M.L., S.M.N., A.R., I.H.M.S, B.A., J.A., E.B.B., D.B., G.B.W., J.B., A.B, S.C., C.T.C., T.A.D., G.V.F., M.G., T.T.H., S.D.M., J.A.O., D.O., V.G.S., O.S., L.S.V., M.W., B.E., L.G., J.H., P.L., E.S.E, M.H., T.M.J, I.G., K.Y., J.L., M.M., K.T., M.L. and K.L. contributed unpublished data and site descriptions used in data analysis. All authors contributed to data interpretation and preparation of manuscript text.

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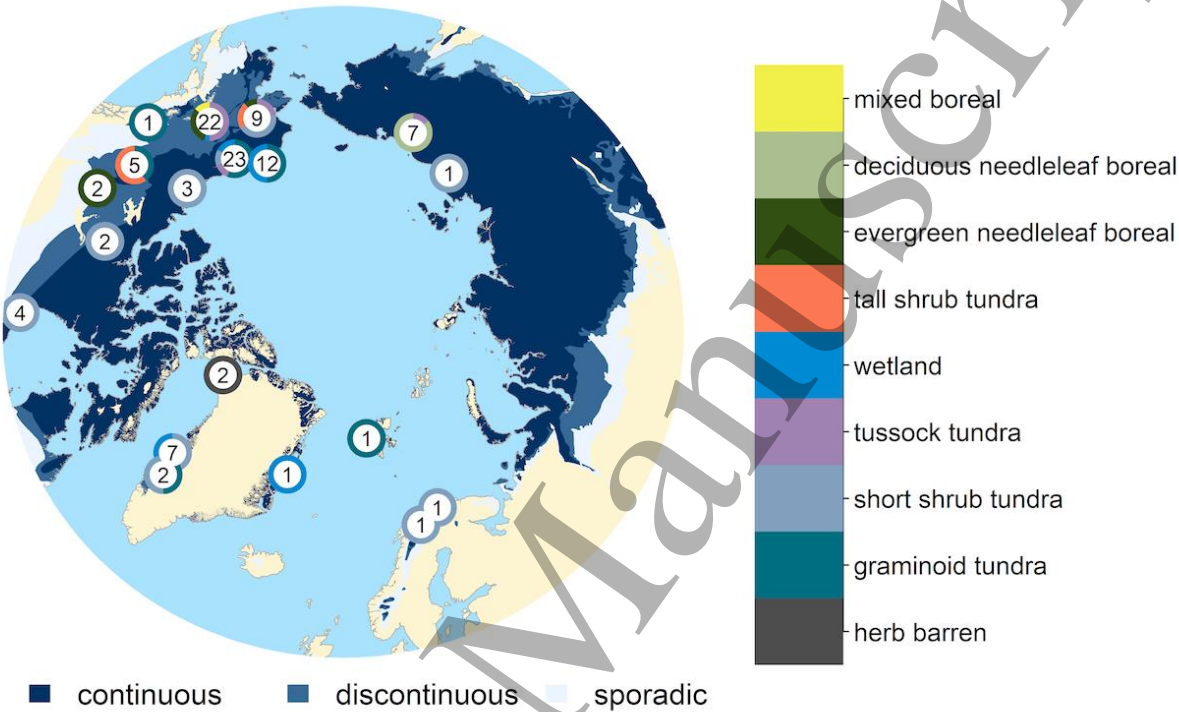
Accepted Manuscript

**Table 1. Summary of site and temperature observations in analysis**

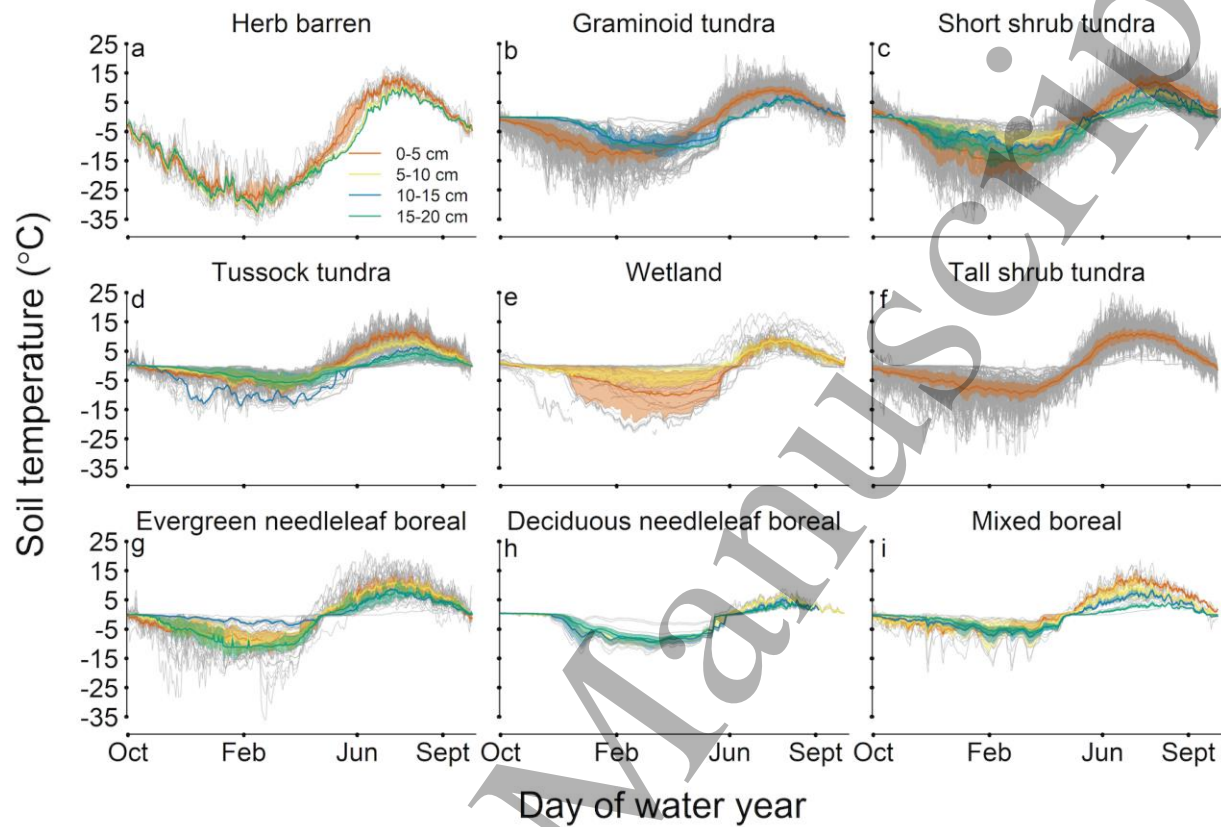
| <i>Vegetation type</i>      | <i>Number of Sites</i> | <i>Site x years</i> | <i>Number of daily soil temperature observations</i> | <i>Number of daily air temperature observations</i> |
|-----------------------------|------------------------|---------------------|--|---|
| Herb-barren                 | 2                      | 9                   | 5,096  | 3,193   |
| Graminoid tundra            | 24                     | 85                  | 68,574   | 33,289  |
| Short shrub tundra          | 24                     | 109                 | 54,520   | 43,476  |
| Tussock tundra              | 17                     | 77                  | 58,520   | 33,609  |
| Wetland                     | 15                     | 35                  | 13,915   | 12,241  |
| Tall shrub tundra           | 5                      | 73                  | 77,372   | 27,058  |
| Evergreen needleleaf boreal | 10                     | 25                  | 16,892   | 10,964  |
| Deciduous needleleaf boreal | 6                      | 9                   | 5,760  | 3,100   |
| Mixed boreal                | 3                      | 7                   | 5,111  | 2,432   |
| <b>Total</b>                | 106                    | 429                 | 305,973  | 169,362   |

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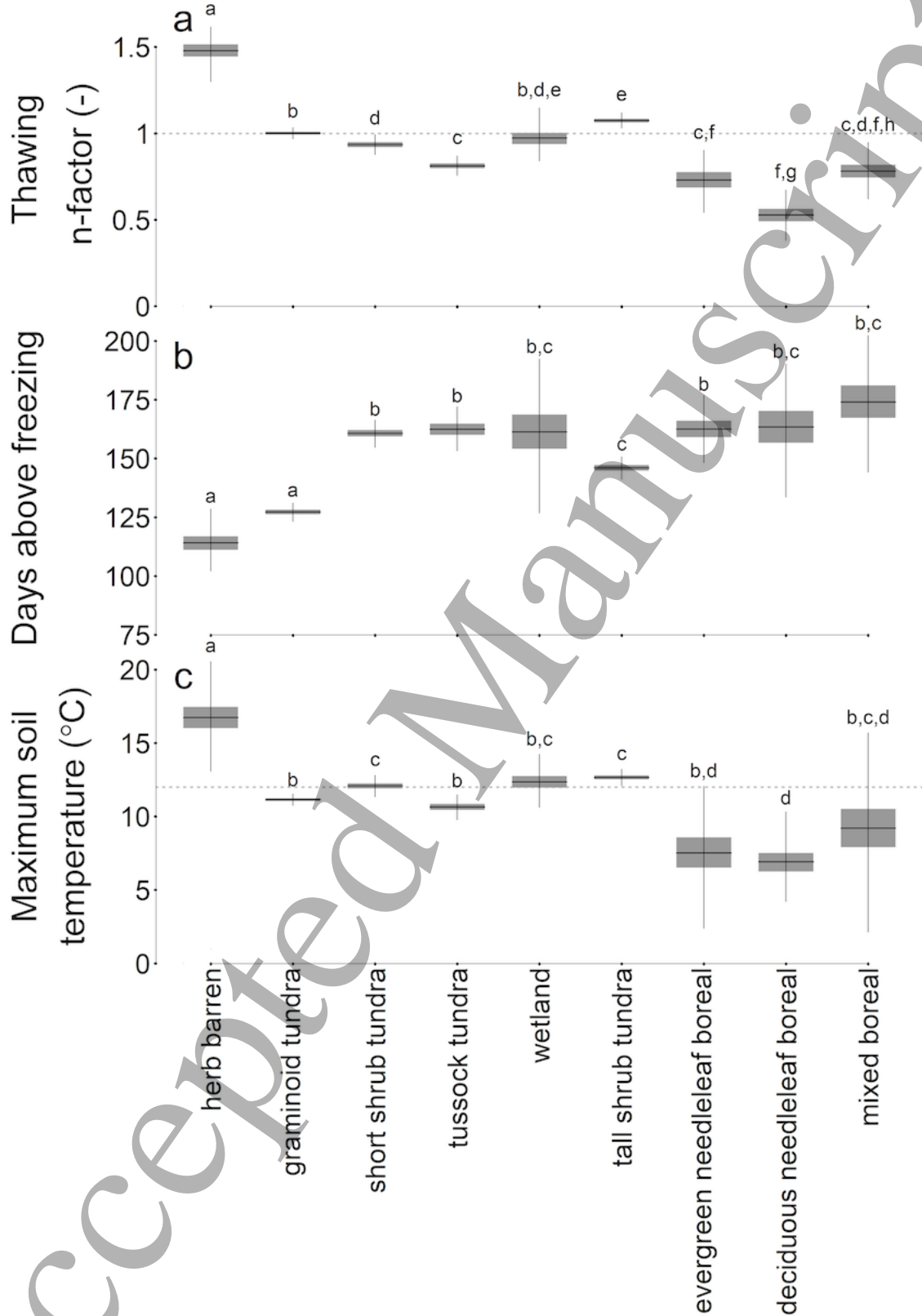
**Figures**



**Figure 1.** Map of study sites for each vegetation type shown with permafrost extent. Geographical locations of study sites are shown with a proportional representation of each vegetation type in a 100 km radius as a single point. The number of sites represented by each point is indicated in the center of the circle.



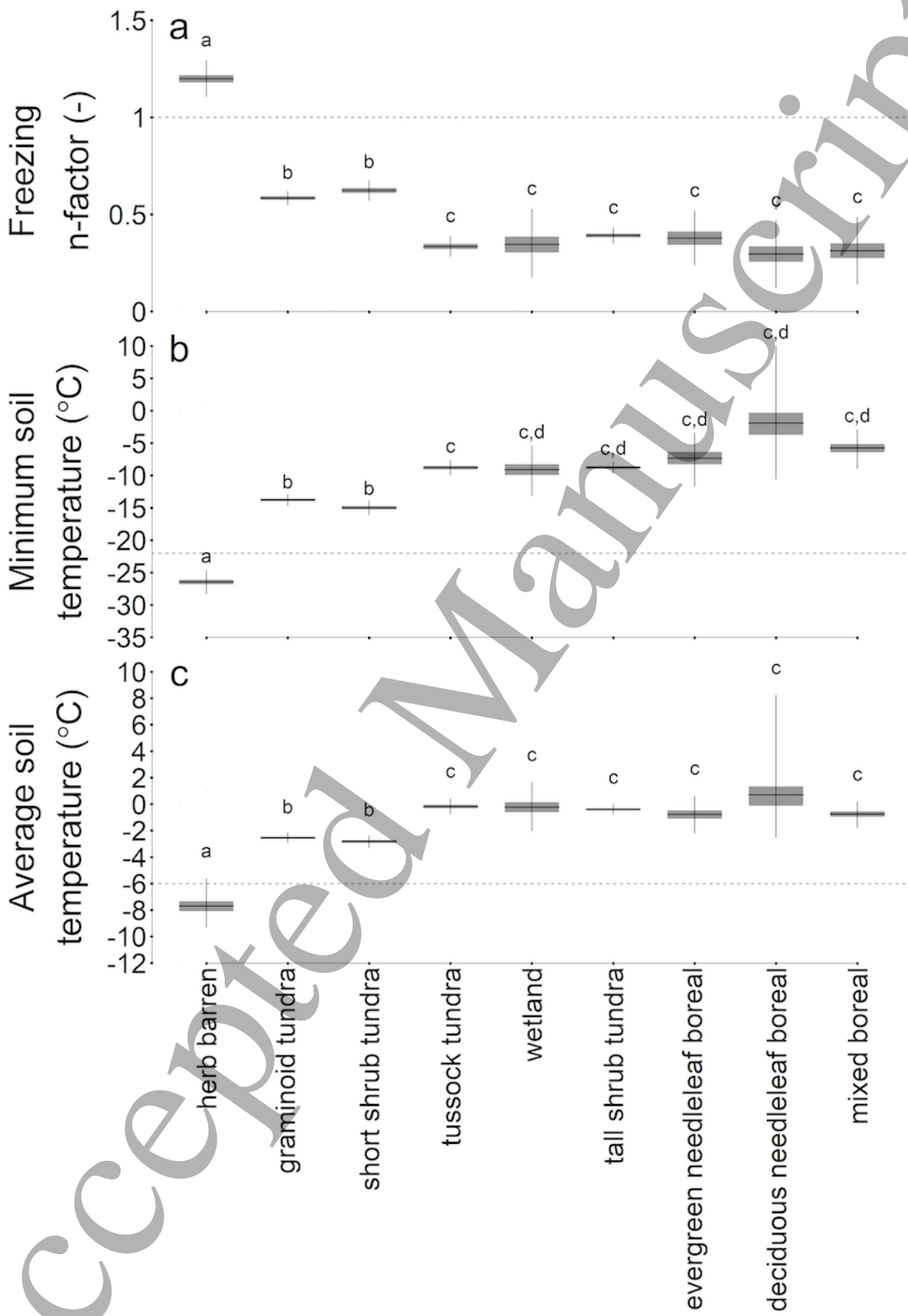
**Figure 2.** Mean daily soil temperature data (0-20 cm) throughout the water year (October-September) for each vegetation type for all observations (grey lines). Mean daily soil temperature within each vegetation type is shown with the 25<sup>th</sup> and 75<sup>th</sup> percentiles for depth increments of 0-5 cm (red), 5-10 cm (yellow), 10-15 cm (blue), and 15-20 cm (green).



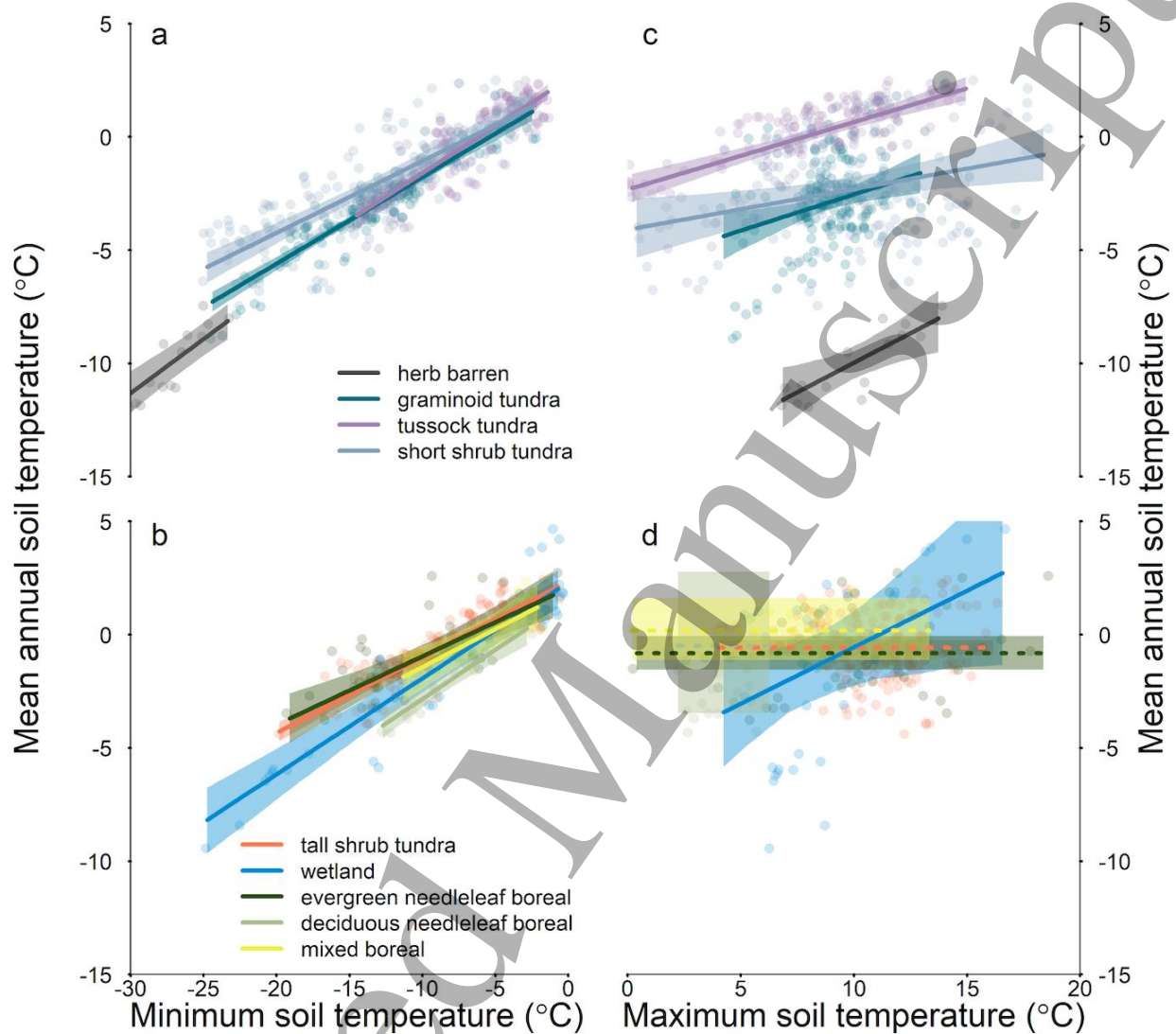
**Figure 3.** Thawing n-factor (a). Mean estimates of number of days in a year above freezing for each vegetation type at a depth of 0 cm (b). Mean annual maximum air temperature for each

vegetation type at a depth of 0 cm and an air temperature maximum of 12 C (c). Boxes contain  
25<sup>th</sup> and 75<sup>th</sup> percent credible intervals and whiskers show Bonferroni corrected credible intervals  
for a 5% significance level used to assess differences between vegetation types.





**Figure 4.** Freezing n-factor (a) for each vegetation type at a depth of 0 cm. Mean annual minimum air temperature for each vegetation type at a depth of 0 cm and an air temperature maximum of -22 C (b). Mean annual temperature for each vegetation type at a depth of 0 cm and an average annual air temperature of -6 C (c). Boxes contain 25<sup>th</sup> and 75<sup>th</sup> percent credible intervals and whiskers show Bonferroni corrected credible intervals for a 5% significance level used to assess differences between vegetation types.



**Figure 5.** Relationship between annual minimum (a, b) and maximum (c,d) soil temperature with average annual soil temperature for each vegetation type. Significant linear relationships for each vegetation type are shown with lines and shaded polygons represent Bonferroni corrected credible intervals for a 5% significance level. Dashed lines show the mean value for the vegetation type when the regression is not significant.